NUMERICAL AND THEORETICAL ANALYSIS OF HYDROMETEOR PROPERTIES OBSERVED BY SPACEBORNE LIDAR AND RADAR

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ABSTRACT

An algorithm to analyze hydrometeor properties from the combination of space-borne radar and lidar data was developed and has been tested with CloudSat/CALIPSO dataset. Sensitivity studies with such observations showed that the uncertainties of the retrieved hydrometeor properties were accomplished within few tens of percent on average for the cases studied. Additionally, of particular interest, the altitude-latitude cross-section of the multiple-scattering factor was investigated along the satellite orbit. This quantity had been implemented in the algorithm to account for multiple scattering for lidar (and radar) in a simplified manner. It was observed that the ranged resolved multiple-scattering factor F varied from 0 to around 0.7, which indicated a large difference in the retrieved cloud microphysical properties in many occasions, if such correction had been disregarded. Further numerical and analytical studies will be provided for the interpretation of the results in relation to the microphysics retrieved in detail, and to assess the limitations and possible improvements of the developed approach.

1. INTRODUCTION

Many algorithms to extract useful information of aerosols and cloud microphysics from polarized mie-scattering lidar have been developed in the past. For instance, global analysis of phase detection of cloud particle types (i.e., phase, configuration) were carried out using CALIPSO lidar to understand the global occurrence of a particular cloud particle type in relation to its generation mechanism [1]. The results are now widely used to evaluate phase discrimination in global models [2] and to study its radiative effects. When combined with cloud radar, comprehensive studies on cloud maco- and micro-physics, their optical properties and cloud dynamics is expected to proceed further on global scales [3], [4].

Among the diverse option of utilizing lidars, retrieval of hydrometeor properties by lidar and radar synergy from space is the central topic of this study. The difficulty and uncertainty of retrieving hydrometeor properties from lidar and radar arises from many factors, for example, attenuation of the signal which leads to insufficient information for the inversion, non-sphericity and in-homogeniety of the constituents, multiple scattering and so on. Recent synergistic methods include schemes to cooperate with such issues [5], and have been evaluated for their use in research. Still, further detailed analysis of the retrieved hydrometeor properties is required. The objective of this study is to investigate the vertical variation of the multiple scattering factor obtained by using the method provided in [5] and the CloudSat/CALIPSO data to assess the limitation of their simple approach taken into consideration for lidar multiple scattering.

2. METHOD

Here the procedure of cloud microphysical retrieval of [5] is briefly reviewed. The input observables are lidar backscattering coefficient β_{obs} and depolarization ratio δ_{obs} at 532 nm for CALIPSO and radar reflectivity factor $Z_{e,obs}$ for CloudSat. The algorithm incorporated a cloud phase classification scheme [1], which uniquely provided a vertically resolved (i.e., 240 m resolution) cloud phase and particle type from these observables. The forward models for lidar and radar were provided in reference to the classified types, and the retrieval of microphysical properties such as effective radius r_{eff} and ice water content IWC were carried out. The observables are related to the outputs at each lidar/radar grid (e.g., for the ice phase case) as follows,

$$Z_{e,obs} = \left[Z_{e,3D}(1-X') + Z_{e,2D}X'\right] IWC \exp(-2\tau'_{ra}) \times \left(\exp\left\{-2IWC\left(\sigma_{ra,3D}(1-X') + \sigma_{ra,2D}X'\right)\Delta R\right\} - 1\right) \Big/ \left(-2IWC\left(\sigma_{ra,3D}(1-X') + \sigma_{ra,2D}X'\right)\Delta R\right) \quad (1)$$

$$\beta_{obs} = \left[\beta_{3D}(1-X') + \beta_{2D}X'\right] IWC \exp(-2\tau'_{li}\eta) \times \left(\exp\left\{-2IWC\left(\sigma_{li,3D}(1-X') + \sigma_{li,2D}X'\right)\Delta R\eta\right\} - 1\right) \Big/ \left(-2IWC\left(\sigma_{li,3D}(1-X') + \sigma_{li,2D}X'\right)\Delta R\eta\right) \quad (2)$$

$$\delta_{obs} = IWC\left(\beta_{cr,3D}(1-X') + \beta_{cr,2D}X\right) \Big/ \left(\beta_{co,3D}(1-X') + \beta_{co,2D}X\right) \quad (3)$$

The definitions of symbols were provided in [5]. In case of ice phase, combination of horizontally oriented and randomly oriented cloud particles [3] [6] were taken into consideration in the algorithm. The equations showed that δ_{obs} is characterized by the mass ratio of IWC for these two typical particle categories to the total IWC (X' and 1-X'), e.g., X'=1 for 100% horizontally oriented ice and X'=0 for completely random orientation [5]. These mass mixing ratios were determined by the difference in the backscattering efficiency for different particle categories [5]. The observables, $Z_{e,obs}$ and β_{obs} are expressed by attenuation ($\sigma_{li,ra}, \tau_{li,ra}$) of Z_e and β at lidar/radar grid due to r_{eff}, *IWC,* and *X'* along the lidar/radar path. The correction for multiple scattering was simply implemented by η factor. Here, η(R) is related to the multiple scattering factor F(R) as 1-F(R) where, $F(R) = \ln\left(P_t(R)/P_1(R)\right)/2\int_0^R \sigma(r)dr$. R is the altitude range, and Pt/P1 is the ratios of the total-to-single scattering contributions [7].

Occasionally, ratio of the region of cloud with radar-lidar overlap to all of the clouds observed from space by CloudSat/CALIPSO may be limited. The algorithm was also formulated to account for the lack of lidar or radar signals in a vertical profile, i.e., retrieval can be performed with insufficient number of observables. The concept was to estimate the possible degree of change in the microphysical properties from one grid to the other within a certain range of accuracy from the differential of β (Ze) among consecutive vertical cloud grids constrained by physical conditions to account for the variation in microphysical properties [5]. In such way, the algorithm avoided using parameterizations that connected observables to the microphysics for the a-priory value at single instrument regions.

3. APPLICATION

3.1 Performance of the microphysical retrieval

The algorithm was applied to the CloudSat/CALIPSO merged data set, which had been released since launch to date and the results were investigated. Note that the cloud-mask for CALIOP for this data set was performed at the original resolutions of CALIPSO level 1B data adopting threshold test for the attenuated total backscattering coefficient at 0.532 μm and a spatial continuity test to avoid the contamination of noise and dense aerosol layers in clouds in an original way [8]. As was seen in [5], CALIOP samples a broad range of clouds characterized with various Ze values, depending on the situation of cloud overlap and the degree of multiple scattering events present (Fig.1). From the CloudSat/CALIPSO dataset, single-instrument region was artificially created from the lidar/radar overlap cloud region to evaluate the microphysical properties retrieved by the algorithm with insufficient number of observables to those with full information. Characterization of the retrieved microphysical properties with CloudSat/CALIPSO data as well as sensitivity studies showed that the algorithm provided a good estimate of the statistics for cloud particle size and hydrometeor mass content. The overall uncertainty of the microphysics retrieval was characterized to be within few tens of percent on average.

3.2 Retrieved η factor

Example of a cloud case shown in figure 1 featured dramatic difference when observed by radar or by lidar. These arose from the difference in attenuation as well the sensitivity to cloud phase (e.g., super-cooled water).

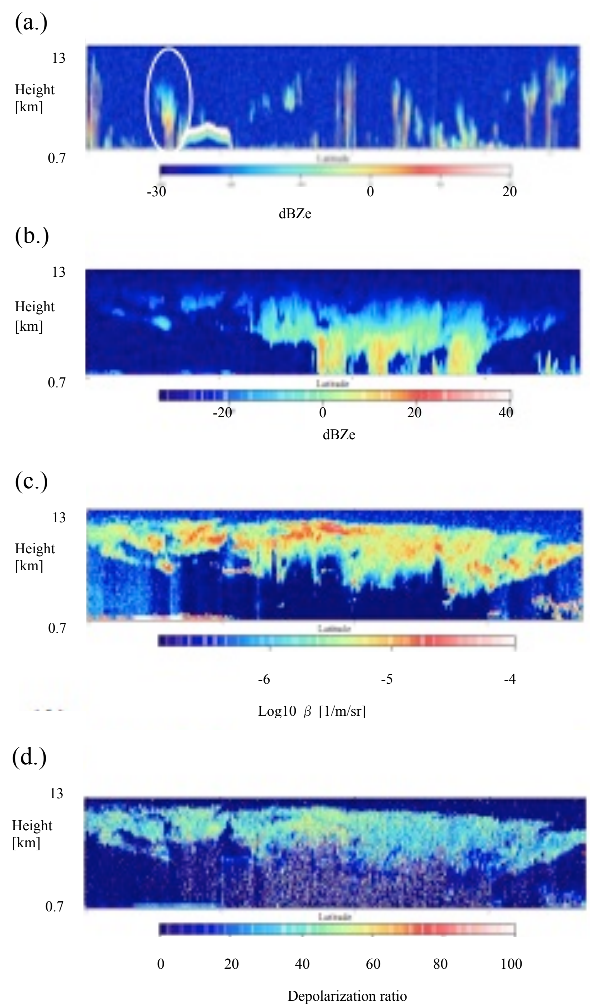

Figure 1 (a) Height-latitude cross section of CloudSat/CALIPSO merged dataset (distributed from Kyushu University) for 1-granule of its orbit. Observed (b) radar reflectivity factor, (c) lidar backscattering coefficient and (d) lidar depolarization ratio for the case studied.

The retrieval result for the microphysical properties and the η factor is shown above about the freezing level for ice phase. The η factor estimated during the microphysics retrieval ranged from about 0.3~1. This corresponded to the contribution from multiple scattering to the total received power of few orders compared to single scattering. This indicated that without the correction, the same combination of $Z_{e,obs}$ and β_{obs} have produced particle size larger by few orders or few orders smaller hydrometeor content if a solution could be found in the first place.

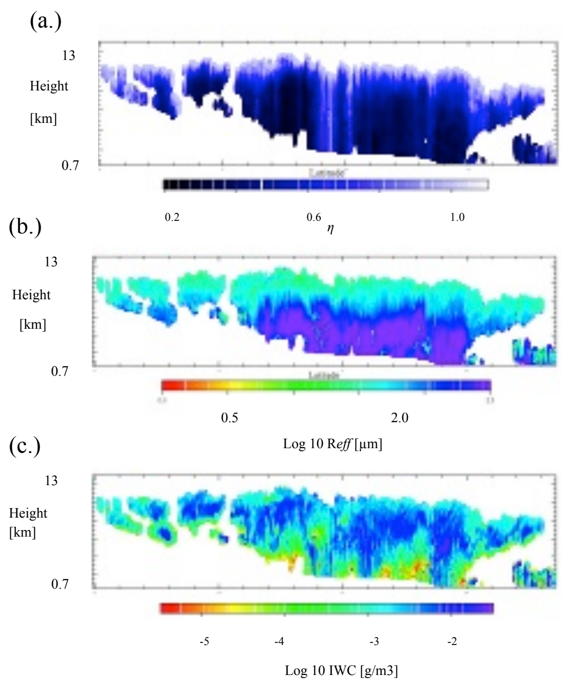

Figure 2. Height-latitude cross section for the retrieved (a) η factor (b) r_{eff} on common logarithms scale and (c) hydrometeor content for cloud/precipitating particles obtained by [5] for the cloud indicated in Fig. 1a. The retrieval results in (a) and (b) are for ice phase.

Currently, further update of the retrieval method is in progress, which is intended to account for multiple scattering from spherical and non-spherical hydrometeors in a more direct way, based on numerical and theoretical studies [7]. This will promote further assessment of the global cloud microphysical property product produced so far from [5] for its use to understand the physics underlain them.

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